A Review of
EPA Region 10 Columbia River Temperature Assessment
Simulation Methods

Prepared for

Bonneville Power Administration

By

HARZA
Engineering Company

September 1999

TABLE OF CONTENTS

1. INTRODUCTION

1.1 Purpose of the Review

In the spring of 1999, the U. S. Environmental Protection Agency Region 10 (EPA) issued an undated memorandum requesting comments to a report entitled, "*Columbia River Temperature Assessment: Simulation Methods*". EPA indicated that the report was undergoing "peer review" and requested comments from Bonneville Power Administration (BPA) and other agencies. The report presents a method to evaluate the contribution of thermal warming of the above river reaches by the dams and impoundments that exist within those reaches. Using existing thermal data sets together with various thermal heat exchange equations, EPA proposes to isolate the effects that dams are having on the thermal conditions in reaches that extend more than 600 miles. They identified the modeled baseline simulation as one that removes all dams below Grand Coulee Dam on the Columbia and all dams downstream of Idaho Power's Hells Canyon complex on the Snake. To place the projects in perspective, the thirteen public projects generate about $3 billion in renewable electricity assets each year with a generating capacity of nearly 14,000 Mw or approximately two Grand Coulee dams. To place the basin in perspective, tributaries contribute discharge from 72 sub-basins in four states and Canada and can contribute flows of over 1 million-cfs at flood stages. Because BPA markets about $2 billion of generated electricity from this Federal Columbia River Power System (FCRPS), they would be affected by any EPA recommendations to remove or modify the operations of this system.

1.2 Authorization

Under existing contract 97AM37234, (BPA) requested Harza Engineering Company to review an EPA model of thermal behavior of the Lower Columbia and Snake rivers. Harza is an international water resources firm that has designed 40,000 Mw of hydroelectric power. In this basin, Harza designed over 2,500 Mw of hydropower now in operation including two mainstem Columbia River dams. During the past eight years, Harza prepared technical reports for the US Army Corps of Engineers, Idaho Power Company, Northwest Power Planning Council and BPA on the FCRPS. Titles include *Analysis of Drawdown of the Four Lower Snake River Projects and John Day Dam*, *Design of Fish Passage Facilities, A Condition Assessment of the FCRPS, A Real Time Model of the Columbia Snake rivers, IDWR Snake River Simulation Model-Daily Time Step* and *Salmon Decision Analysis.* Thus Harza is familiar with the operation of the FCRPS (Columbia and Snake system) including fishery and environmental issues. Harza has also developed several sophisticated modeling tools to simulate and predict hydrothermal behavior of rivers and reservoirs. Examples include the Dynamic Reservoir Simulation Model for the proposed Watana/Devil's Canyon high dams in Alaska and the real time Missouri-Madison River model now in review by FERC EIS. What follows is Harza's independent review of the EPA thermal modeling effort.

1.3 Background of the EPA Model

The U.S. Environmental Protection Agency (EPA) Region 10 *Columbia River Temperature Assessment: Simulation Methods* draft report (Yearsley, 1999) uses a sophisticated numerical solution method to estimate daily-averaged water temperature on the main stem of the Columbia and Snake Rivers (Figure 1). Kalman filter theory and reverse particle tracking are used to estimate the *System State* of water temperature using a hybrid one-dimensional linear state-space model. The solution method employed by the EPA consists of a systems model, two thermal energy equations, and an observations model which uses sets of compiled and modified water temperature and flow observations for the Columbia and Snake rivers (McKenzie and Laenen, 1998). In this experimental model, two applications of the Kalman filter are evaluated through examination of the innovation sequences, i.e., the time series of differences between the observations and the model predictions before updating. The first application estimates the *System State* (water temperature) using simulated flow conditions based on the current configuration of hydroelectric dams and their impoundments on the Columbia and Snake Rivers. The second application of the model estimates the *System State* using hypothetical flow conditions based on the removal of all dams and related impoundments.

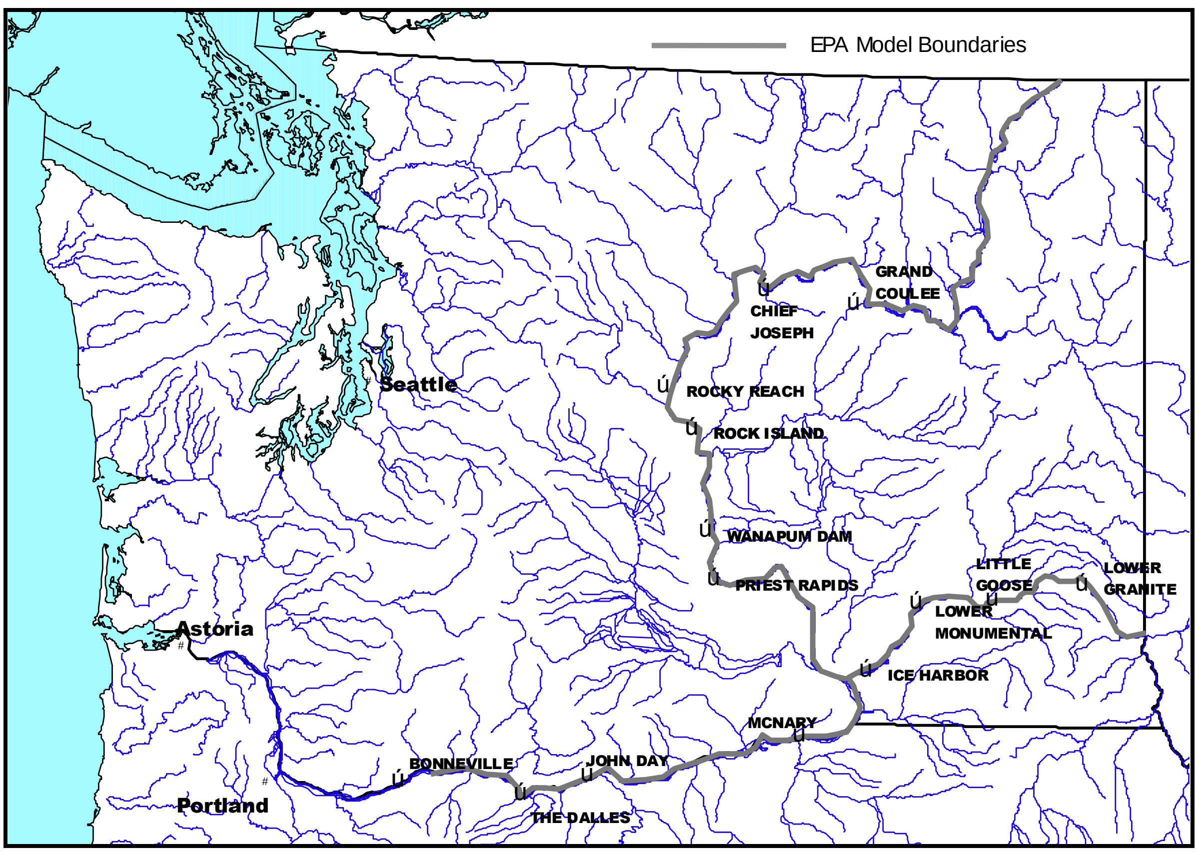

Figure 1. Main stem of the Columbia and Snake rivers used in the EPA Thermal Model showing the extents of the model boundaries in bold.

1.4 Harza's Approach to the Review

Harza's objectives are to describe the mathematical origins of the EPA model and to discuss its application as an environmental screening tool for TMDL assessment. Water quality screening models are decision support tools for assessing large geographic areas or a wide variety of water quality parameters for the purpose of identifying specific areas requiring further study (Barnwell and Krenkel, 1982). Inherent to Harza's objectives are a thorough analysis of the assumptions used in the simulation and a description of the statistical uncertainty of the model. Key issues based on our review include the use of the Kalman filter for parameter estimation, exclusion of groundwater return flow from the system water balance analysis, and autocorrelation of the 30-day moving average for water temperature innovations sequence. In a properly tuned Kalman filter, one expects the innovation sequence to be white (uncorrelated, with zero mean). A white innovation sequence can thus be taken as an indication that there is no further information to be extracted from the sequence of observations. Autocorrelation of the water temperature innovations sequence indicates possible structural problems with the numerical model itself.

The stated objective of the EPA study is to develop a mathematical model of water temperature that can be used as a screening tool for assessing and managing water-quality limited segments on the main stem of the Columbia and Snake rivers. In water quality limited segments the state is required to establish a total daily maximum load (TMDL) for pollutants contributing to the impairment of beneficial uses. Two of the most frequently listed parameters on the Washington Department of Ecology Candidate 1998 Section 303 (d) List are total dissolved gas and water temperature. Actions that contribute to increased water temperatures include:

- Silviculture and agricultural practices that modify upper watersheds through the removal of shade trees adjacent to tributary rivers;
- Irrigation practices and groundwater withdrawals;
- Stream manipulations such as channelization which results in wider and shallower streams;
- Point source industrial and municipal wastewater discharges.

The TMDL assessment process by definition requires the analysis of both point source and non-point loading sources when assessing water-limited segments. Non-point source contributions to changes in the thermal regime of the Columbia and Snake Rivers would include an analysis of the modifications of the watershed due to agricultural and silvicultural practices. However, the model only assesses the relative contribution of impoundments and selected tributaries to changes in water temperature of the Columbia and Snake Rivers. Other potential sources of impairment, such as modifications in the watershed, are ignored which calls into question the validity of the model as a water quality-screening tool to develop a TMDL assessment.

Harza believes it is important to recognize the inconsistencies of the EPA's goals and objectives as defined within the Columbia River Temperature Assessment: Simulation Methods report. The primary achievement of this study is to document the development of a prototype numerical water temperature model that uses Kalman filter theory for parameter estimation. The model is elegantly defined, but experimental in nature. Viewed in this context the results of the EPA study show that Kalman filter theory is potentially applicable to the domain of estimating water temperature; however, significant work needs to be done on testing the optimization character of the filter, mapping the spatial distribution of systems model error, and applying empirical methods for improving the initial estimates of model parameters. Harza has assessed the various components of the solution method including the assumptions, error terms, data inputs, parameter estimation process, and the sensitivity analysis of the simulation process over this very large and complex geographic region. Based on this analysis we describe the appropriateness of the application of this model as a water quality-screening tool, the results of the modeling process, and identify issues requiring further study.

2. ANALYSIS OF THE EPA WATER TEMPERATURE MODEL

2.1. Temporal and Spatial Boundaries of the Model

The temporal and spatial boundaries of the model include the system boundaries and the time and length scales of the LaGrangian step. The boundaries of the hydrologic system include the Columbia River from the International Border to Bonneville Dam and the Snake River from its confluence with the Clearwater River near Lewiston, Idaho to its confluence with the Columbia River near Pasco, Washington. System boundaries for run-of-the river reservoir segments in the model are from the tailwaters of Grand Coulee dam to Bonneville Dam and from Snake River mile 130.0 to 0.0. Run-of the-river reservoirs are those for which reservoir elevation is assumed to be constant and water coming into the reservoir is passed directly through the reservoir.

The lower time scale boundary for the water temperature input data is equal to or greater than one day with the upper boundary being 21 years. The boundaries are constrained by the existing hydrologic and meteorological data available for the Columbia River system under existing management. Length scales for physical river segments are driven by the need to achieve computational stability and accuracy in the model. Other factors include the availability of geometric data and spatial variability in the river geometry for the Columbia and Snake River systems. The driver for length scales is the calculated travel time for a parcel of water to traverse a given computational segment in a day, which is dependent upon simulated flow conditions. The EPA report does not provide sufficient discussion or documentation on how the model addresses the issue of spatial variability in river geometry.

2.2. Kalman Filter Theory and Application

The Kalman filter provides the general solution to the recursive, minimized mean square estimation problem within the class of linear estimators. In layman terms, assume there is some physical process that is running and you are interested in the state of this process. The state of this process in this instance is the change in water temperature in the main stem of the Columbia and Snake rivers. However, it might also be the number of fish in the sea, the position of an aircraft etc. With observation data of this physical process the task is then to estimate the state of the process based on your observations. To do this requires a mathematical model of the physical process and a mathematical model of how the observations are linked to the physical process. The Kalman filter is one applicable method to estimate the state of the physical process based on the observations.

The Kalman filter has been used extensively for many diverse applications such as navigational and guidance systems, radar tracking, sonar ranging, and satellite orbit determination. The Kalman filter gives a linear, unbiased, and minimum error variance recursive algorithm to estimate the unknown states of a dynamic process from noisy data taken at discrete real-time intervals. States, in this context, refer to any quantities of interest involved in the dynamic process, e.g. water temperature, position velocity, chemical concentration, etc. For Gaussian random (normally distributed) variables the Kalman filter is the optimal linear predictor-estimator. For variables of forms other than Gaussian (non-normally distributed data) the estimator is the best only within the class of linear estimators.

2.3. The Systems Model: Thermal Energy Budget Approach

The EPA uses a thermal energy budget model to simulate daily average water temperatures in the main stem of the Columbia and Snake Rivers as a function of longitudinal distance. The solution technique being used is a mixed Eulerian-LaGrangian model which employs the concept of a one-dimensional reverse particle tracking to implement the LaGrangian step. A LaGrangian frame of reference moves with the water; whereas, the Eulerian concept employs a reference system fixed in space through which the water flows. The EPA rationale for using a mixed Eulerian-LaGrangian model is that it provides flexibility to expand the scope of the model to include diffusion-like processes. It avoids instabilities in the solution when the Courant stability criterion is exceeded, and it reduces the prediction of water temperature to a single variable.

The current structure of the EPA one-dimensional thermal model ignores diffusion-like processes and divides the river into N segments with water temperature values recorded only on the boundaries between segments. Heat exchange across the air-water interface is considered the major source of thermal energy for lakes, rivers, and reservoirs. Although the thermal energy budget approach for aquatic ecosystems is well supported in the literature (Brown, 1969; Brown, 1970; Cole and Buchak, 1997; Foreman et al., 1998) the integration of Kalman filter theory to estimate the Systems State is novel and experimental for the purposes of TMDL assessment. The EPA study assumes the net exchange of the thermal energy across the air-water interface for the Columbia and Snake River systems can be described by the following equation (EPA equation 4):

$$H_{NET} = (H_S - H_{RS}) + (H_A - H_{RA}) + H_{EVAP} + H_{COND} - H_{BACK}$$

Where,

H_{NET} = Net heat exchange across the air-water interface
H_S = Shortwave solar radiation
H_{RS} = Reflected shortwave solar radiation
H_A = Longwave atmospheric radiation
H_{RA} = Reflected atmospheric radiation
H_{EVAP} = Evaporative heat
H_{COND} = Conductive heat flux
H_{BACK} = Blackbody radiation from the water surface

2.4. The Observation Model

The observation model for the EPA simulation of water temperature at the K^{th} time step using Kalman filter theory is provided by Gelb (1974) and consists of the following terms:

$Z_k = H_k T_k + V_k$

Where,

Z_k = the measured value of the water temperature, degrees Centigrade
H_k = the measurement matrix
V_k = the measurement error

The Kalman filters requires knowledge of the second-order statistics of the noise of process being observed and of the measurement noise in order to provide the solution that minimizes the mean square error between the true state and the estimate of state. In this case the measurement noise is the analysis of the water temperature dataset of McKenzie and Laenen (1998). Kalman filtering provides a convenient means of determining the weightings (denoted as gains) to be given to input measurement data. It also provides an estimate of the estimated state's error statistics through a covariance matrix. Hence the Kalman filter chooses the gain sequence and estimates the estimated state's accuracy in accordance with the variations (in terms of accuracy and update rate) of input data and modeled process dynamics.

2.5. Parameter Estimation

Parameter estimation is a common problem in many areas of process modeling, both in on-line applications such as real time optimization and in off-line applications such as the modeling of reaction kinetics and phase equilibrium. The goal is to determine values of model parameters that provide the best fit to measured data, generally based on some type of least squares or maximum likelihood criterion. In the most general case, this requires the solution of a nonlinear and frequently nonconvex optimization problem. The EPA process for parameter estimation of the state-space equations for water temperature is a three-step process:

1. Estimate the deterministic parameters, which in this case are the components of the heat budget and the advected thermal inputs from tributaries. The travel times for the water parcels are also implicitly determined from a one-dimensional analysis of the system hydraulics including lakes and reservoirs.
2. The estimated deterministic parameters are adjusted until the simulated results from the systems model are approximately unbiased. The bias is assumed to be minimized when the mean of the innovations sequence is small.
3. Estimate the variance of the systems model.

It is not uncommon for the objective function in nonlinear parameter estimation problems to have multiple local optima. However, the standard methods used to solve these problems are local methods that offer no guarantee that the global optimum, and thus the best set of model parameters, has been found. The EPA model does not provide adequate documentation to determine if the best set of model parameters have been found. This fact is especially disturbing since the EPA did not conduct any tests to determine the optimization of the Kalman filter.

2.6. Data Sources

It is helpful to step back from the mathematical manipulation of the EPA water temperature simulation process and first assess the quality of the model as a function of the quality of the basic source data. The EPA model is based on a one-dimensional hydraulic and thermal energy, reverse particle tracking, model for estimating the state variable water temperature. Boundary conditions for the model include the Columbia River from the International Border to Bonneville Dam and the Snake River from its confluence with the Clearwater River near Lewiston, Idaho to its confluence with the Columbia River near Pasco, Washington. The key data used as input for the model includes the following:

- Water temperature data records for the Columbia and Snake Rivers were assembled by McKenzie and Laenen (1998) and represent the key data input values for the EPA water temperature model. This water temperature dataset is very important since it provides the basis for estimating the probabilistic parameters of the measurement model used in the simulation. The data reviewed by McKenzie and Laenen (1998) were obtained from powerhouse scroll case measurements made in conjunction with total dissolved gas monitoring at dams. The accuracy, bias, and variability of these data vary considerably from site to site with bias measurements as high as 2.0 degrees C and variability as high as 2.0 degrees C. The phenomena of "stepping" is readily apparent in the data that is constant over a period of several days.

- River geometry data characterizes the hydraulic properties of the river as a function of flow and time. The input requirements for the simulation are water depth, water width, and cross-section averaged velocity as function of river flow. Sources for this information include results of a water surface profile computation using the HEC-RAS Model Series, cross-sections from previous studies at a very limited number of locations, and NOAA Navigation Charts.
- River hydraulic/hydrology data are required to estimate the hydraulic coefficients for both modeling simulation scenarios, that is hydraulic coefficients with the dams in place and with the dams removed.

2.7. Key Assumptions of the Simulation Methods

Based on the size and spatial heterogeneity of this hydrologic system a number of simplifying assumptions is used in the modeling process. The key assumptions include:

- The model is one-dimensional in that it predicts daily averaged water temperature as a function of longitudinal distance. Although never specifically defined it is assumed that the particle being tracked is flowing on the top of the water surface at the mean elevation of the river segment.
- The model ignores the effects of dispersion on simulated daily averaged water temperature during the LaGrangian step.
- The Kalman filter is used to estimate the parameters of the linear systems model which is a hybrid Eulerian-LaGrangian state-space equations for water temperature
- The Kalman filter is a linear predictor and the extended Kalman filter is used to estimate non-linear estimates of state.
- The observations model uses scroll case measurements and measurements made at several monitoring stations in conjunction with total gas monitoring where the temperature probe is located at a depth of ten feet or greater below the surface of the water.
- Water temperature stratification effects are ignored for the run-of-the-river reservoirs with the exception of Lake FDR.
- Initial conditions for water temperature on both the main stem of the Columbia and Snake rivers, as well as their major tributaries, were estimated by regressing observed water temperature on the week air temperature.
- Particle traveling speeds and river system geometry are based on the assumption that one-dimensional gradually varied, steady-state flow methods, are appropriate for the main stem of the Columbia and Snake rivers in both model cases i.e., the case with dams in place and the case with dams removed.

3. DISCUSSION OF THE MODEL APPLICATION

3.1. Validity of the Model Heat Budget

3.1.1. Radiation Budget

The EPA thermal model for the main stem Snake and Columbia Rivers uses a commonly implemented energy budget algorithm to estimate various surface energy parameters. Short wave solar radiation and long wave atmospheric radiation components are estimated based on the site latitude, the declination of the sun, the day of the year, percent cloud cover and other factors. The EPA does not specify exactly which parameters are incorporated into this estimation nor does the EPA document the degree of accuracy obtained using these equations. Recent field data collection on the Madison River (Harza, 1995) indicate these types of estimation schema tend to be over generalized. We have found that in thermal modeling situations, where a reasonable degree of accuracy is required using environmental variables such as cloud cover estimates, these estimates tend to be less reliable and inconsistent. This is primarily due to the difficulty in estimating percent cloud cover and the variation in atmospheric radiation that occurs under similar rates of percent cloud cover.

3.1.2. Evaporative Heat Flux

The EPA model uses a fairly contemporary evaporative heat flux formulation which estimates evaporation rate as a function of wind speed, vapor pressure difference, and a host of other parameters which are not specified in the report. Such formulae can be considered valid in general terms, although the result depends heavily on the accuracy of water temperature, air temperature, the relative humidity of the overlying air mass, the wind speed, and the barometric pressure. These variables were not known with any reasonable certainty when the analysis was conducted. Hence, significant error in the estimation of these values, and the subsequent evaporative heat flux estimates is likely, and undetectable in the EPA analysis. Under certain conditions, evaporative heat flux is a strong contributor to the overall surface energy exchange budget. This is particularly true during daylight conditions when the water is warmer and the relative humidity is relatively low. Errors in estimating this contribution can produce substantial error in estimating the actual net energy exchange at the air-water interface.

3.1.3. Convective Heat Flux

The term convection describes any heat transfer process between two media when at least one of the media is a fluid. The EPA model utilizes a convective heat flux equation that is quite old but still widely used in many conventional models. This formula is essentially a pressure corrected, linear function relating evaporation rate (vapor pressure difference) to the temperature difference between the air and the water surface. Conventional theory states that the air blowing over the water surface will create a boundary layer. This layer consists of a thin film of air that is cooled by the water to the air dew point temperature. Having cooled to the dew point temperature, the boundary layer air is in equilibrium with the water surface.

The final dew point temperature is changed somewhat from that of the ambient air because the water surface may add water vapor to (or subtract vapor from) the boundary layer, thereby changing the "apparent" relative humidity within the boundary layer. It is also assumed that the air is supplying some of the heat required to vaporize the water molecules since both the boundary layer air and the water surface are cooled during the process of evaporation. The final net rate of heat flow across this boundary layer then supposedly depends on the temperature difference between the ambient air and the dew point temperature, and the evaporation rate. A major assumption made in applying this theory is that a boundary layer will always form in which the air in the boundary layer indeed comes to equilibrium with the water surface. While this may be a likely condition for large water bodies (like oceans), it is probably not the case for smaller water bodies (like rivers), and unlikely in the case of very small water bodies (like evaporation pans sitting right next to modern weather stations).

Typically, models using this approach will couple the evaporation rate and the convection rate equations. The convection rate depends in part on the rate obtained for evaporation. This is obvious from equation 20 in the EPA model. Suppose that ($\mathbf{e_s}$ -$\mathbf{e_a}$) = 0 in the denominator of equation 20. This would signify a condition where the vapor pressure of the air and the vapor pressure of the water surface were equivalent. At that point, equation 20 would predict an infinite convection rate. While it is true that in such a case the convection rate would be infinitely larger than the evaporation rate (which would be zero), clearly the convection rate is never "infinite". This condition is avoided by defining the convective heat flux in terms of the evaporative heat flux.

There are certain inherent problems with using such an approach. First, the entire application hinges on the not necessarily valid assumption that the air in the boundary layer always comes to equilibrium with the water surface. The approach also assumes that all of the heat energy acting to accomplish the vaporization process is supplied by the overlying air mass. This is not the case. The evaporation process is driven by a pressure gradient. Specifically this pressure gradient arises due to the difference between the vapor pressure exerted by the water surface and the vapor pressure exerted by the water vapor in the overlying air mass. Thermal convection is driven by a temperature gradient. Specifically this gradient is the difference between the temperature of the water surface and the temperature of the overlying air mass. Empirical studies conducted by Harza have demonstrated conclusively that virtually all of the energy expended to vaporize water molecules at the water surface is supplied by the water. For these reasons, it is not physically justifiable to express the convection rate in terms of the evaporation rate.
The approach also relies heavily on being able to obtain an accurate prediction of the evaporation rate, or, at least, the vapor pressure difference. Being able to accurately determine the vapor pressure difference requires being able to determine the local relative humidity,

barometric pressure, air temperature, and water temperature with reasonable accuracy. Wind speed is another variable which plays an important role.
We recommend an alternative approach that does not allow coupling of evaporation and convection rates (Harza, 1995). This has been especially useful in the case of smaller water bodies, such as rivers, where the air properties remain relatively unaffected by the presence of the water body. We tend to utilize models that express the convection rate in terms of the air-water temperature difference, relative humidity, barometric pressure and wind speed. Harza model routines also express evaporation formula in terms of relative humidity, air temperature, water temperature, barometric pressure and wind speed. In the case of the convection formula, the barometric pressure and relative humidity data are used only to correct for variability in the heat capacity of the air. Using such a procedure, Harza has developed a more accurate and physically realistic model that allows decoupling of evaporation and convection rates.

3.2. River Hydraulics

The second crucial phase of any river modeling effort involves accurate characterization of river hydrology. Being able to accurately determine the surface area, volume, and flow rate of any individual segment of river reach is a critical prelude to calculating the temperature response under a particular thermal stimulus. While a screening model may make generalized assumptions about the similarity of widely spaced geographic points, any attempt to accurately characterize large numbers of river reaches spanning hundreds of miles, based on a handful of calibration measurements, will always yield widely varying (and often dubious) levels of accuracy. Harza has developed thermal models where it has proven difficult to characterize stream hydrology along a stretch of river covering twenty miles without extensive cross-section and hydraulic data. Similar quantitative data sets applied to river reaches spanning hundreds of miles would certainly produce results of even greater questionable accuracy.

Riverine thermal models attempting to predict small changes of a few degrees or less require carefully constructed hydrologic components to estimate the mass of water being acted upon by a specific rate of energy flux. Errors in estimating this mass inevitably lead to errors in determining the temperature response under a given energy input. Regardless of what particular river model is applied, a corresponding energy balance can always be found which will yield acceptably accurate calibration against a base condition. It is during the extrapolation of conditions different from the base condition where it is imperative that hydrology/hydraulics, and meteorology/net energy flux closely track true responses. For river hydraulics, any variations in slope, depth, channel roughness, channel width, the presence of canyons, cliffs and other natural obstacles, will all serve to introduce uncertainty into the hydraulic component of the analysis. Clearly not all of these variables can be addressed by a handful of "representative" cross-sectional measurements.

3.3. Statistical Manipulation of Input Data

Various input data for the EPA model are synthesized, extrapolated, averaged over wide time intervals, and statistically modified. Such an approach is understandable as a method for making a first approximation as a broad initial screening assessment. However, results based on these assessments should be viewed with caution and skepticism, since the model basis is experimental and data simulation techniques are partially hypothetical. Additionally, one-dimensional flow models fail to account for varying velocity profiles in the transverse direction especially when the river is wide and non-prismatic. Models in the HEC-RAS family tend to over simplify flow conditions occurring in a large, deep-channeled river. Water parcels moving through the center channel may travel at rates considerably faster than those along the shore. As a result, this simplified model tends to suggest a monotonic temperature regime in what is really a complex geographic and temporal setting of varying thermal conditions.

4. CONCLUSIONS

- The result of the EPA simulation of water temperatures in the main stem of the Columbia and Snake rivers is based on processed observed data of the river system using Kalman filter theory. This model ignores non-point sources in watersheds, including the entire middle and upper Snake River watersheds, which impact the thermal regime of the Columbia River system. Specifically, the impacts of agricultural and silviculture modifications such as shade tree removal, stream modifications, and ground water withdrawal and recharge are ignored. At this point in time the model should be considered experimental in nature and not suitable to adjudge the thermal contributions of dams in isolation of all other watershed features that affect water temperature.
- The lack of testing for Kalman filter optimization coupled with the apparent autocorrelation of the 30-day moving average for the water temperature innovations sequence suggests there may be significant structural problems with the model. A discussion by the EPA of methods to assess the optimization of the model would prove helpful in assessing what additional data is required to develop a reasonable TMDL assessment tool. For example, would the inclusion of high-resolution empirically derived hydrologic parameters improve the tuning of the Kalman filter.
- The EPA does not address the spatial variability in the river geometry nor does it provide adequate documentation on the conceptual flow model for the scenario with dams removed. Of particular concern is the lack of documentation on the system water balance. The estimation of hydraulic coefficients using HEC steady-state gradual flow conditions does not account for seasonal flux nor is the statistical procedure well documented in the EPA model.

5. RECOMMENDATIONS

1. Kalman filter techniques experimentally used herein are widely accepted in different scientific and technical disciplines, such as navigation and GPS, and offer new insights into the estimation of time series systems of state. However, if the EPA Kalman filter thermal model receives additional federal funding for research, we recommend that other federal agencies affected actively participate.. BPA may even wish to obtain the EPA source code and begin an independent assessment of the model's potential to incorporate spatially

varying parameters that reflect both non-point (i.e agricultural, runoff, forestlands etc) as well as tributary (watershed) thermal contributions to the system.

2. A thermal model based on high-resolution empirically derived data should be developed for key reaches of the Columbia and Snake rivers. The objective would be to independently identify watershed sources affecting water temperature and link them to land-use practices such as the modification of stream channels or removal of shade trees. Spatial scales should be at the hydrologic unit code (HUC) level with a goal of aggregating estimated contributions to thermal modifications of the Columbia and Snake river system. Harza (1994; 1995) used precise meterological, hydraulic and water temperature data on the Missouri-Madison river system for the sole purpose to measure reservoir contribution to the thermal environment of the river. The data/model was also capable of predicting the geographical extent dam removal or changed operations could reduce temperature. Previously collected data was almost useless in this regard because it was a "stew" of concatenated data sets collected at various times by different organizations and never uniformly calibrated. This increased uncertainty as to the causes of the problem.

3. Because of the magnitude of the basin BPA, EPA the Corps and other involved agencies should embark upon a coordinated and unified program to collect calibrated data needed to understand the physical effects of hydro operations on the Lower Snake river and the main stem Columbia River System. Data collection should be stepped up and modified to include a contemporary suite of precise, continuous meteorological data, accurate flow data, and more rigorous thermal data sets that can corroborate some of the questions posed by EPA. BPA should gain a sound understanding of the effects of watershed wide practices on river temperature.

4. The region should also consider development of a highly accurate deterministic heat transfer model. Such a thermal model, coupled with a more precise flow model, would be capable of predicting the effects of a wide range of river operations including dam removals. Federal agencies would also have the capacity to (1) determine more effectively what operational changes would improve temperature and (2) be able to optimize their overall operations to better meet temperature as well as other needs of the system. Such a tool could simulate a range of alternatives such as controlled releases at Dworshak Reservoir, or the modification of Brownlee Dam outlet works to allow selective withdrawal and hypolimnetic releases. It would also allow assessment of irrigation withdrawals and returns, the effects of temporary drawdowns and to more accurately determine thermal contributions and mitigation from the reservoirs.

5. The inclusion of tri-level thermograph data collected across river transects would improve the analysis of spatially variable water temperature conditions. We know that fish do not see the river as homeothermic. Both adults and juveniles selectively use deep water, shallow water, open water and shorelines during different phases of their migrations. More complete understanding of the three-dimension thermal structure of the data coupled with hydrologic measurements collected at the same geographic and temporal scales would improve modeling results and the associated biological interpretations.

6. REFERENCES

Barnwell, T.O., Jr. and P.A. Krenkel. 1982. The use of water quality models in management decision making. *Journ. of Water Sci. and Tech*. 14 1095-1107.

Brown, G.W. 1969; Predicting temperatures of small streams. *Water Resourc. Res*., 5(1), 68-75.

Brown, G.W. 1970; Predicting the effect of clear cutting on stream temperature. *J. Soil Water Conser*, 25, 11-13

Cole, T.M. and E.M. Buchak, 1997;A two dimensionally laterally averaged, hydrodynamic and water quality model. Version 2.0. USACE, waterways Experiment Station, Vicksburg, Mississippi.

Foreman, M.G.G., C.B. James, M.C. Quick, P. Hollemans and E. Wiebe. 1997. Flow and temperature models for the Fraser and Thompson Rivers. Atmosphere-Ocean, 35(1), 109-134

Gelb, A., J.F. Kasper, Jr., R.A. Nash, Jr., C.F. Price and A.A. Sutherland, Jr. 1974. *Applied Optimal Estimation*, 374 pp., MIT Press, Cambridge, Massachusetts

Harza, *Madison River Temperature Study, Final Phase II Report* for Montana Power Company. May 1994.

Harza, *Madison River Temperature Study, Pulse Flow Test Report* for Montana Power Company. October 1994.

Harza, *Thermal Analysis of the Lower Madison River* for Montana Power Company. June 1995.

McKenzie, S.W. and A. Laenen. 1998. Assembly and data quality review of available continuos water temperature for the main stems of the lower and mid-Columbia and lower Snake Rivers and mouths of major contributing tributaries. NPPC Contract C98-002, Northwest Power Planning Council, Portland, Oregon.

Yearsley, J.R. 1999. Columbia River temperature assessment: simulation methods. EPA Region 10, Seattle, Washington.